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AN ALL-SOLID CRYOCOOLER TO 100K BASED ON OPTICAL REFRIGERATION IN YB:YLF CRYSTALS

Mansoor Sheik-Bahae

University of New Mexico
Department of Physics and Astronomy
1919 Lomas Blvd., NE
Albuquerque, NM 87131

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Final Report

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3550 Aberdeen Ave SE
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KEVIN KOWALCHUK
Program Manager

//SIGNED//
PAUL D. LEVAN, Ph.D.
Technical Advisor, Space Based Advanced Sensing and Protection

//SIGNED//
BENJAMIN M. COOK, Lt Col, USAF
Deputy Chief, Spacecraft Technology Division
Space Vehicles Directorate

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Optical refrigeration has become the only solid-state refrigeration mechanism capable of reaching cryogenic temperatures. With the coldest solid-state temperatures (T >185K from 300K) achievable by optical refrigeration, it is now timely to apply this technology to cryogenic devices. Along with thermal management and pump absorption, this work addresses the most key engineering challenge of transferring cooling power to the payload while efficiently rejecting optical waste-heat fluorescence. We discuss our optimized design of such a thermal link, which shows excellent performance in optical rejection and thermal properties.

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1. Summary

Optical refrigeration has become the only solid-state refrigeration mechanism capable of reaching cryogenic temperatures. With the coldest solid-state temperatures (T >185K from 300K) achievable by optical refrigeration, it is now timely to apply this technology to cryogenic devices. Along with thermal management and pump absorption, this work addresses the most key engineering challenge of transferring cooling power to the payload while efficiently rejecting optical waste-heat fluorescence. We discuss our optimized design of such a thermal link, which shows excellent performance in optical rejection and thermal properties.

2. Introduction

Task 1. Demonstrate laser cooling in Yb:YLF crystal to 100K with >100mW of heat lift.

Since the reports of major milestones in optical refrigeration by cooling below the so called Peltier barrier of ~170K and the National Institute of Standards and Technology (NIST) cryogenic barrier of 123K, optical refrigeration achieved record cooling to 115K using a 10% Yb:YLF crystal. Due to the high purity and high doping of the 10% Yb:YLF crystal, cooling was anticipated below 100K. A Brewster cut crystal was fabricated with dimensions 4x4x12 mm^3, which was characterized with an external quantum efficiency of 99.6% and background absorption of 2.0×10^{-4}cm^{-1}, corresponding to a global minimum achievable temperature (gMAT) of 93K (Figure. 1 right) at 1020 nm corresponding to the E4-E5 transition in the Yb^{3+} Stark manifold, Figure 1 (left).

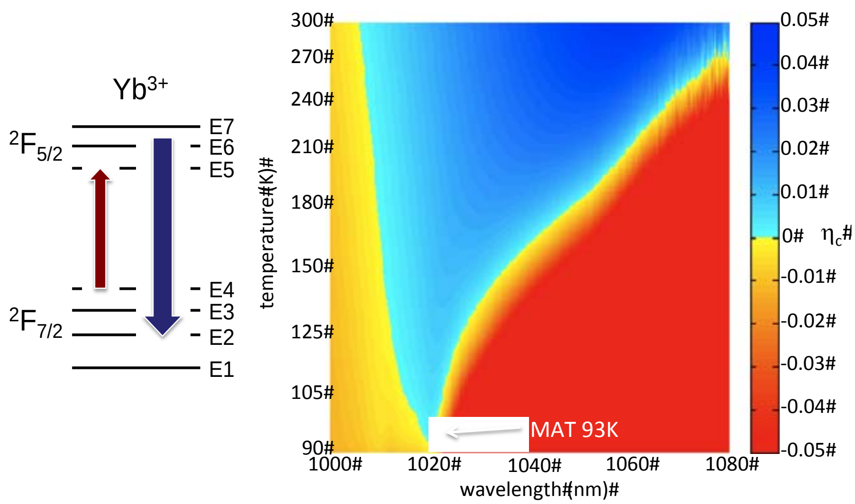

Figure 1.Stark manifold and cooling efficiency contour plot

The sample was placed between two mirrors creating a non-resonant cavity to enhance pump absorption, and inside a clamshell to reduce ambient heat loads. The crystal cross-section and cavity geometry allowed for 14 passes through the crystal, an increase of 75% above previous experiments. Due to the increased absorbed power, caused by both the increase in passes and high doping concentration of the crystal, a new clamshell assembly was designed and machined out of oxygen-free high conductivity (OFHC) copper, and coated with a solar selective coating. The original coating, Maxorb, was exchanged for a new coating, Acktar Nano Black, which has improved fluorescence absorption and low emissivity properties. The new clamshell design improved upon previous clamshell iterations by increasing efficiency at which fluorescence energy is extracted, allowing for more precise control of the crystal environment and reduced radiative heat load, resulting in lower crystal temperatures.

A 60W IPG Photonics Yb-fiber laser is used to pump the crystal at full power, of which 54W is incident on the crystal after interaction with alignment optics and pump back-reflection isolation. Saturation is intentionally avoided through careful focusing geometry entering the non-resonant cavity. Cooling resulted in a new record cooling achievement of 93K, the first result below 100K and matching the anticipated gMAT of the crystal where the cooling efficiency approaches zero. At 100K, the cooling efficiency is 0.48%, where an estimated 20W of absorbed power results in 96mW of cooling power.

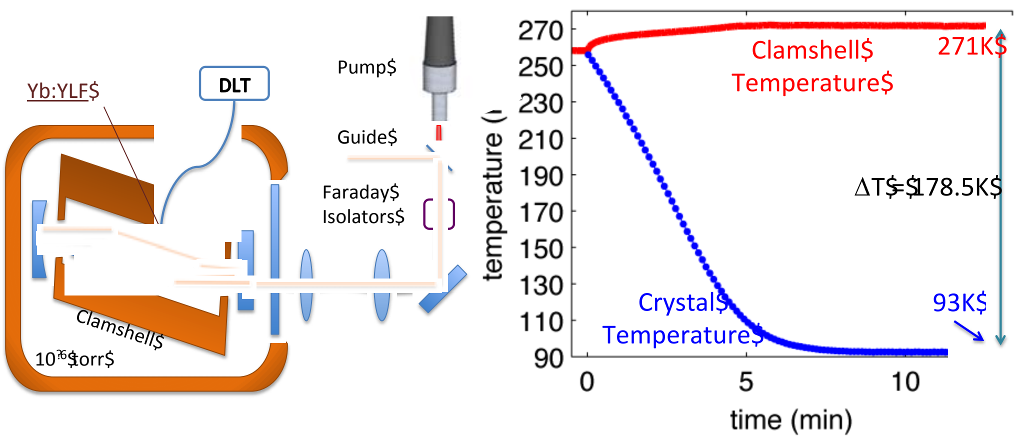

Figure. 2. Experimental setup and temperature measurement (left) Schematic of experimental setup;(right) cryogenic bulk cooling by optical refrigeration results.

Under steady-state conditions, cooling power is equal to the heat load. Because the full power of the laser is used, the limit of cooling power is being utilized. Therefore the clamshell temperature was maintained at 271K , reducing the heat load, which is equivalent to an increased cooling power, in order to achieve gMAT. Under the same conditions, maintaining the clamshell at 295K results in cooling to 102K. Crystal temperature is measured by differential luminescence thermometry (DLT).

3. Methods, Assumptions, and Procedures

Task 2. *Fabricate and test a sapphire thermal link based on our tapered-kink technology.*

The purpose of a thermal link is to optically isolate an applied load from the high power fluorescence generated by the optical refrigeration process, as well as provide a pathway of high thermal conductivity to remove heat from the load. Initial thermal link designs were analyzed with Zemax, a ray tracing software, to determine the optical rejection of various thermal link shapes, Figure. 3.

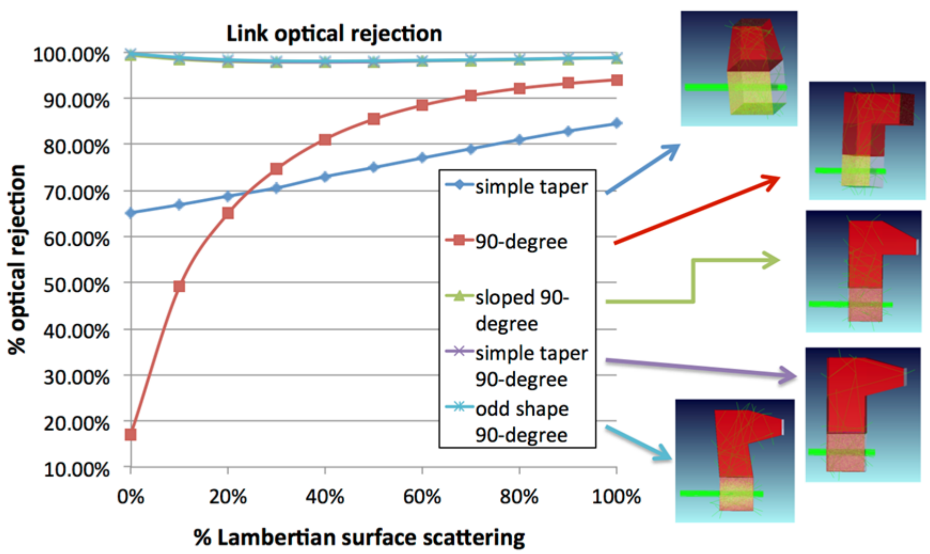

Figure 3. Plot of optical rejection as a function of lambertian surface scattering with images of the thermal link shapes to the right.

As the link complexity increases, the optical rejection improves. In this study, only link shapes, which can be easily fabricated in the lab are considered. However, by increasing the number of "kinks", the link will provide increased optical rejection at the cost of slightly reduced thermal conductivity. Optical rejection should surpass 99% with increased number of kinks. With a modeled understanding of the optical rejection in place, a fused silica link was fabricated to experimentally verify the optical rejection properties prior to implementation of a high thermal conductivity link made of sapphire.

4. Results and Discussion

The fused silica link is cut and slightly polished, to help ensure cleanliness, from a high quality fused silica window. The size is matched to a 5% Yb:YLF crystal and is bonded to the crystal with a ultra violet UV curable optical adhesive. At this stage it is understood that the thermal properties will be far from desirable, with a thermal gradient between the cooling crystal, the UV adhesive, and the thermal link as seen in Figure 4 (left), but it is a necessary step toward understanding the optical properties of the thermal link (right) Color image.

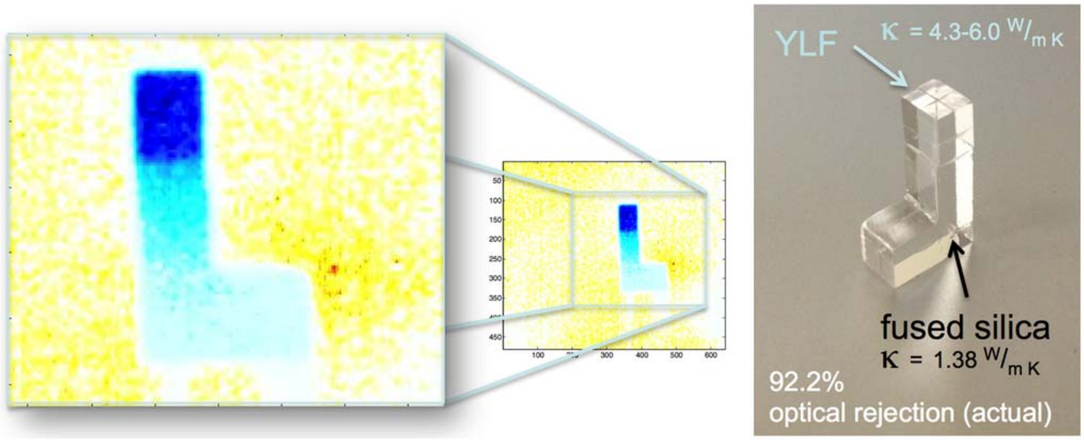

Figure 4. (left) Thermal images of the fused silica thermal link bonded to a 5% Yb:YLF crystal highlighting a significant discontinuity in cooling at the adhesive interface.

The optical rejection measurements require precise determination of the fluorescence generated that enters the thermal link, as well as the total fluorescence incident on the thermal link end. Measurements are therefore taken using a large area silicon detector, which closely matches the surface area of each face being analyzed, 3x3 mm^2, coupled with shielding to prevent spurious fluorescence and external sources of light from altering the measurement, as well as index matching fluid between the measured face and the detector to ensure consistent photon counts by removing total internal reflection. Experimental measurements of 92.2% optical rejection match well with ZEMAX models where a simple 90^o kink should provide between 92%-94% optical rejection for the given surface quality.

5. Conclusions

With models matching experimental measurements of a fused silica link, the next step of fabricating a high conductivity thermal link from sapphire was undertaken, Figure 5 (left). Two significant improvements are utilized. First, a thermal link is fabricated out of sapphire, which has nearly 30x higher thermal conductivity than fused silica. Second, the thermal link is Van Der Waals bonded to a piece of 10% Yb:YLF crystal, removing the adhesive thermal barrier. The same optical measurements undertaken for the fused silica link are performed for the sapphire link with 92.9% optical rejection.

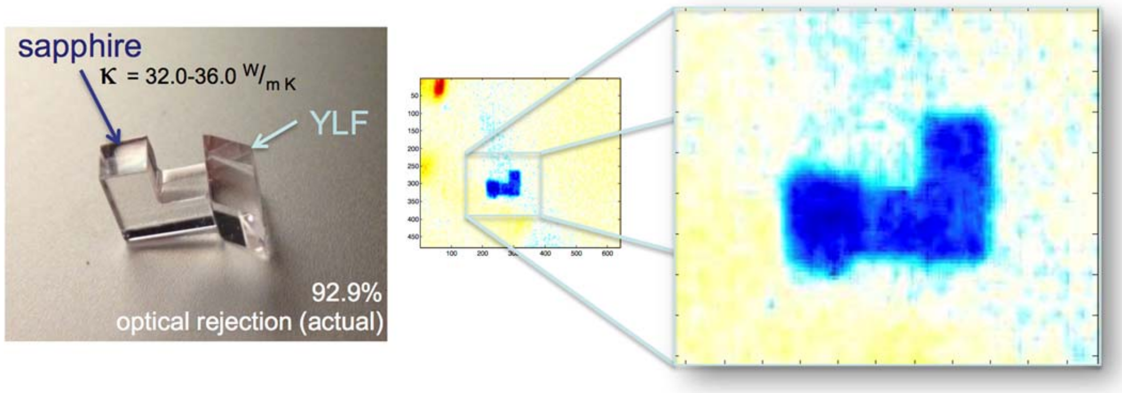

Figure 5. (left) Color image of the sapphire thermal link; (right) Thermal images highlighting no thermal discontinuity.

A significant improvement in thermal properties is measured for the sapphire thermal link, Figure 5 (right) compared to the fused silica link, Figure 4 (left). When measured quantitatively, Figure 6, it can be seen no thermal barrier exists for the Van Der Waals bonded sapphire link, while adhesive imposes significant impedance. Additionally, no thermal gradient exists along the length of the sapphire link, thanks to the high thermal conductivity, whereas the fused silica link exhibits a significant gradient.

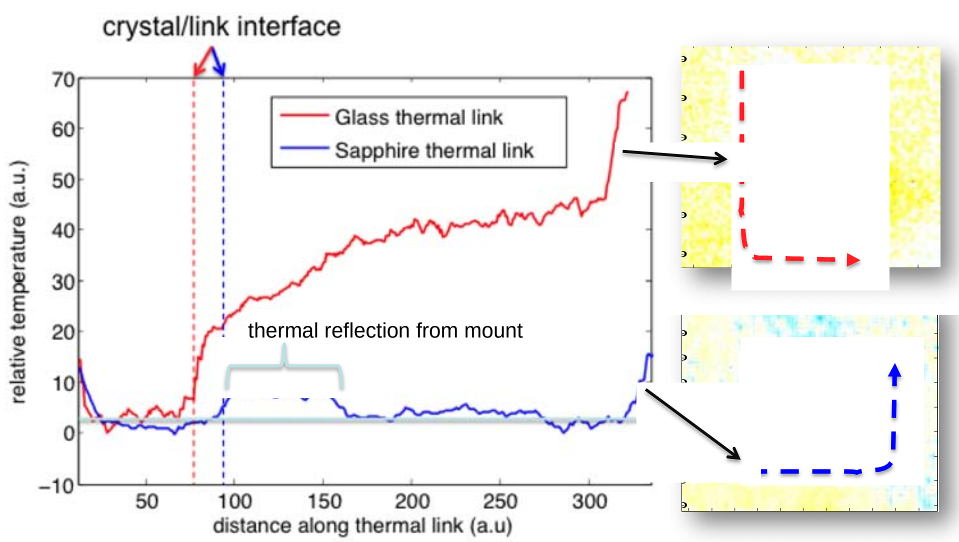

Figure 6. Thermal profile of the fused silica (red) and sapphire link (blue).

6. Recommendations

It should be noted that thermal reflections from the lab environment can generate errors in the thermal image for sapphire. Even though the errors are reduced, a slight bump in the thermal image is detected due to a reflection from the mount, and could not be completely removed. Instead the reflection was placed at a portion of the link where it can be reasonably omitted, since it should be understood that the link end cannot be physically colder than the portion nearest the crystal, and therefore the link is uniformly cold.

To further understand the consequence of the addition of a thermal link to the cooling performance of Yb:YLF, a room temperature cooling efficiency test was performed. Here positive cooling efficiency denotes heating, and the increase in cooling efficiency at long wavelengths characterizes the background absorption. Because this is the first bonding of sapphire to YLF, it was not known if the Van Der Waals bond could withstand cleaning. Therefore a before and after cleaning test cooling efficiency test was performed, Figure 7, finding that the bond can indeed withstand cleaning, and that the cooling efficiency of the original crystal is nearly recovered. In the case for the 10% Yb:YLF crystal bonded to a sapphire thermal link, a gMAT is anticipated to be 100K, which can perhaps be improved with a second round of cleaning.

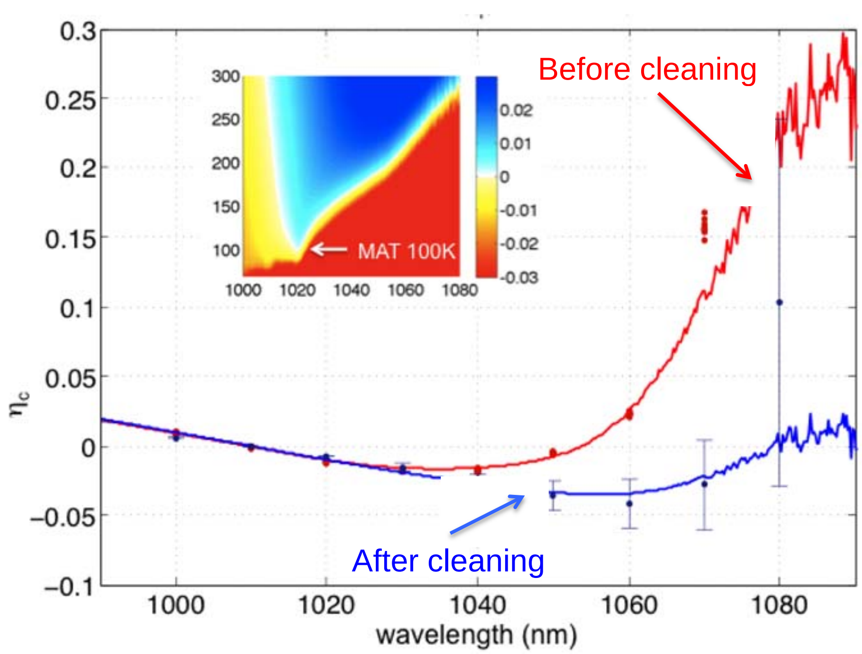

Figure 7. Sapphire link cooling efficiency after cleaning

List of Acronyms

DLT	Differential luminescence thermometry
gMAT	Global minimum achievable temperature
NIST	National Institute of Standard and Technology
OFHC	Oxygen-free high conductivity

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